

The Ages of the Lunar Seas

(Apollo data/geomorphic indices)

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ABSTRACT Two ages are attributed to each circular lunar sea, the age of formation of the circular basin, probably by impact, and the age of the filling of the basin by lava-like effusions.

Each lunar-sea surface displays a range of geomorphic indices. This is interpreted as being due to the presence of effusions of different ages on the surface of each sea. The landing sites of Apollo 11 and 12 have geomorphic indices of value 10.3 and 8.4. The radiometric ages of the rocks are, respectively, approximately 3.65×10^9 and 3.36×10^9 years. The range of geomorphic indices on sea surfaces is from less than 5 to more than 14, which indicates that the two Apollo crafts landed on surfaces formed about in the middle of the total span of time of sea-surface formation. Using four possible relationships between geomorphic index and age, I conclude that the age of the youngest effusions is less than 3×10^9 years and the age of the oldest effusions is more than 4×10^9 years. The results of the analyses of the Russian Luna 16 samples, although preliminary, fit in this interpretation.

In any discussion of lunar seas, care must be exercised in differentiating between the two concepts sometimes erroneously implied in the term *mare*, i.e., the dark surfaces, relatively smoother than the surrounding *terrae*, and the basins over which the material constituting the dark surface was deposited. In the cases of the *circular maria*, as for example Imbrium, Serenitatis, Nectaris, Humorum, and Crisium, it is generally accepted that the basins are the scars left by impacts. In other cases, like Oceanus Procellarum, the dark material was deposited over a regular preexisting topography. The difference between the two concepts is clearly shown by Mare Nectaris. If the term sea is applied only to the dark material, this is a relatively small sea of about 9.7×10^4 km². But, if the term applies to the basin, then the sea extends to the Altai Escarpment and has an area of about 50×10^4 km². In other words, the Nectaris Basin is only partially covered by the dark material. The possibility of the existence of completely uncovered sea basins was mentioned when the first pictures of the far side of the moon were obtained (1).

It is evident that each circular basin has two ages: the age of the basin, presumably formed by impact, and the age of the dark material, presumably lava-like effusions. Hartmann (2) has convincingly shown that the time interval between the impact and the effusions was considerable. The purpose of this paper is to show that the effusions themselves lasted for an extremely long time, at least 10^9 years. These results are presented with the kind permission of the Geological Society of America, in whose bulletin a more detailed report will be published.

GEOMORPHOLOGY OF THE SEA EFFUSIONS

Previous work (3) led to the development of a method to quantitatively describe the geomorphology of lunar surfaces. A function was determined that relates the number density of craters (excluding ghost craters) to the number of these craters that are essentially uneroded. The value of this function in different areas was defined as the *geomorphic index* of that area. This index describes a lunar area better than the number density of craters because it combines two independent parameters—number density of craters and erosional stage.

An analysis of the areal distribution of geometric indices shows that basically two erosional processes operate on lunar craters. The first process causes a *continuous* degradation of a crater through consecutive stages. Micrometeoritic impact, space erosion, and perhaps isostatic recovery are probably the main agents. The second process is *discontinuous*, as it can affect craters belonging to any stage of the continuous sequence. Sea effusions, volcanism, ballistic sedimentation, and seismic energy created by large impacts in the vicinity are the main agents.

Another process is occasionally superimposed on the two degradation sequences, and this is *rejuvenation*, which occurs when all the craters in an area are obliterated, either by deep sea effusions or by the effect of a very large (sea-basin forming) impact in the vicinity.

When an area is rejuvenated by sea effusions, meteoritic impacts will show the passage of time on its surface, i.e., the geomorphic index will be a monotonic function of the crystallization age of the uppermost effusion. This is not true for craters belonging to the discontinuous degradation sequence and for areas affected by successive processes of rejuvenation by large impacts. However, these difficulties do not present an insurmountable problem as most of the sea-producing impacts occurred early in lunar history, before the sea effusions, and craters of the discontinuous sequence are easy to identify. As a result of these considerations one can be confident that for most of the sea surfaces, the geomorphic index will be a monotonic function of the crystallization age of the uppermost effusion.

The range of the geomorphic index for sea surfaces is from less than 5 to more than 14. The landing sites of Apollo 11 and 12 have geomorphic indices of 10.3 and 8.4, respectively. This suggests that the two crafts landed on surfaces formed about in the middle of the total span of formation of the sea surfaces.

It is of interest to notice that the surface of each sea does not have a constant index, but ranges in almost all cases from

the minimum value of less than 5 to the maximum of more than 14. This suggests that the effusions did not proceed to consecutive seas after termination of the activity in the preceding seas, but occurred alternately or contemporaneously. In geologic terms, one can state that the sea effusions have an interfingering time-stratigraphy.

Two seas, Humorum and Nectaris, have no surfaces of low geomorphic index, and Nubium shows only a minimum amount. A preliminary interpretation is that the effusive activity did not stop on all seas at the same time.

The oldest surface is found in Fecunditatis. It is, however, impossible to state that the effusive activity did not start on all seas at the same time because the absence, or small amounts, of old surfaces in some seas may simply be due to burial by younger effusions.

A slight indication exists that the effusive activity on the front side of the moon, when viewed *in toto*, had two maxima. The most common geomorphic indices have values of 5-6.5 and 8-9.5. It is impossible to say whether this is significant or is purely due to statistical fluctuations. If truly there were two maxima in the effusive activity of the moon, this would have a significant effect on any theory of lunar development.

PRELIMINARY AGES OF SEA EFFUSIONS

It would be of considerable interest to translate the geomorphic index of sea surfaces into years. The radiometric ages of the rock samples collected by Apollo 11 and 12 are, respectively, about 3.65×10^9 and 3.36×10^9 (4, 5). An infinite number of curves can be drawn through two points, but it is likely that the relationship between index and age is within the limits determined by a linear and a logarithmic expression. Four possible curves were drawn: the linear relationship between (i) index and age, (ii) logarithm of the index and age, (iii) the index and the logarithm of the age, and (iv) the logarithm of the index and the logarithm of the age. The span between the extreme curves, drawn for the extreme values of the radiometric ages, gives the probable range of age for each value of the geomorphic index.

The results, preliminary but indicative, are as follows:

(a) the youngest sea effusions have an age of less than about 3×10^9 years;

(b) the oldest sea effusions have an age of more than about 4×10^9 years;

(c) the two maxima of effusive activity, if present, occurred between 2.6 and 3.1×10^9 and between 3.3 and 3.5×10^9 years ago.

Recently, more results of the Russian Luna 16 mission have become available. The geomorphic index of the landing site is

14.3. If we assume again that the relationship between index and age is within the extreme curves described above, this index corresponds to an age between 4.0 and 4.5×10^9 years. The age of the collected crystalline rocks was given by Academician A. P. Vinogradov to have an age of definitely more than 4×10^9 years (A. P. Vinogradov, "Preliminary Data on Lunar Ground brought to Earth by Automatic Probe Luna 16", Addition to the Abstracts of the II Lunar Science Conference, Houston, Texas, Jan. 11-14th, 1971). Although this result is preliminary, it is encouraging to see the agreement.

Mutch (6) concludes that all results can be grouped into one of two general theories. One is Urey's "dead"-body model (7), in which the mare material is caused by surface melting, essentially contemporaneously for each sea. The other general theory is the one followed by the U.S. Geological Survey and was basically developed by Shoemaker and Hackman (8), and Gault (9). In this theory, the lunar surface continues its geological evolution throughout most of the lunar history. The results here presented are in agreement with the latter view.

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